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The U.S. Navy's Fleet Numerical Oceanography Center has several operational products available for thermal structure nowcasts in the northeast Atlantic/Norwegian Sea. These include regional nowcasts in the northeast Atlantic/Norwegian Sea. These include regional nowcasts and short forecasts at 40 km resolution, global nowcasts and short forecasts at 190 km resolution, and two thermal climatologies at 50 km and 380 km resolutions. We propose two hypotheses: (1) that the inclusion of real-time data in the nowcasts and forecasts improves nowcast skill over the use of climatology alone and (2) that increased real-time product resolution increases nowcast skill. This study addresses these hypotheses by comparing the six products listed above in the northeast Atlantic/Norwegian Sea region on a seasonal basis.

We extracted daily bathythermograph (BT) data from the real-time operational database in a 2,000 km diameter region centered on the Iceland-Faeroe Front from July 1989 through June 1990. We then compared each BT to the spatially-interpolated results from each of the six operational products. All comparisons were made prior to the BTs assimilation into the real-time products. For each season, we then accumulated three months of results to form a root-mean-square deviation of a given product relative to the verifying BTs.

In this region, the results indicate that the real-time nowcasts perform better than both climatologies in autumn and winter. The results also demonstrate the advantage of increased resolution in fall and winter, but not as strongly. The spring and summer results do not produce definitive conclusions.

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A Seasonal Skill Comparison between Operational Ocean Thermal Structure Products in the Northeast Atlantic/Norwegian Sea

PAPER

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ABSTRACT

The U.S. N. vy's Fleet Numerical Oceanography Center has several operational products available for thermal structure nowcasts in the northeast Atlantic/Norwegian Sea. These include regional nowcasts and short forecasts at 40 km resolution, global nowcasts and short forecasts at 190 km resolution, and two thermal climatologies at 50 km and 380 km resolutions. We propose two hypotheses: (1) that the inclusion of real-time data in the nowcasts and forecasts improves nowcast skill over the use of climatology alone and (2) that increased real-time product resolution increases nowcast skill. This study addresses these hypotheses by comparing the six products listed above in the northeast Atlantic/Norwegian Sea region on a seasonal basis.

We extracted daily bathythermograph (BT) data from the real-time operational database in a 2,000 km diameter region centered on the Iceland-Faeroe Front from July 1989 through June 1990. We then compared each BT to the spatially-interpolated results from each of the six operational products. All comparisons were made prior to the BTs assimilation into the real-time products. For each season, we then accumulated three months of results to form a root-mean-square deviation of a given product relative to the verifying BTs.

In this region, the results indicate that the real-time nowcasts perform better than both climatologies in autumn and winter. The results also demonstrate the advantage of increased resolution in fall and winter, but not as strongly. The spring and summer results do not produce definitive conclusions.

INTRODUCTION

Fleet Numerical Oceanography Center (FNOC) is the U.S. Navy's production center for global-scale and open-ocean regional-scale oceanographic products. FNOC produces many real-time nowcasts and forecasts of ocean thermal structure on a daily basis. These products range from the global domain at 190 km resolution down to specific regions at 20 km resolution and serve a number of military and civilian uses. They can provide the following: (1) three-dimensional thermal structure for input to acoustic propagation models used in anti-submarine warfare, (2) surface boundary conditions for operational atmospheric models, (3) front and eddy locations and vertical thermal structure for fisheries applications, and (4) a thermal history of the ocean for use in global climate studies.

FNOC has a suite of products that can be applied to the above purposes (Clancy and Sadler, 1992). The most appropriate of these depends on the question being asked. One might pose the specific question, "What is the best product to represent today's thermal structure?" In the Norwegian Sea area, six different thermal structure products are available that might be chosen as the "best" nowcast representation. These include global and regional nowcast products (specifically designed for nowcasts), global and regional short forecast products, and two different climatologies. Given this choice of products, the imperative for objective measures of relative skill becomes obvious.

Previous comparisons of unassimilated thermal data with a Mediterranean regional and a global nowcast indicate that (1) both Mediterranean and global nowcast products perform better than the global climatology (Clancy et al., 1986; Clancy et al., 1992) and (2) increased resolution provides significant improvement to nowcast skill (Clancy et al., 1992). Harding et al. (1991) report similar results in the northeast Atlantic/Norwegian Sea region for the February/March/April 1990 period using the six operational products listed above.

This present study extends this last work by examining the data available from July 1989 though June 1990 to derive a seasonal picture of the relative nowcast skill of the six products in the northeast Atlantic/Norwegian Sea. The results of this study also provide a statistical benchmark for planned future product improvements in this region.

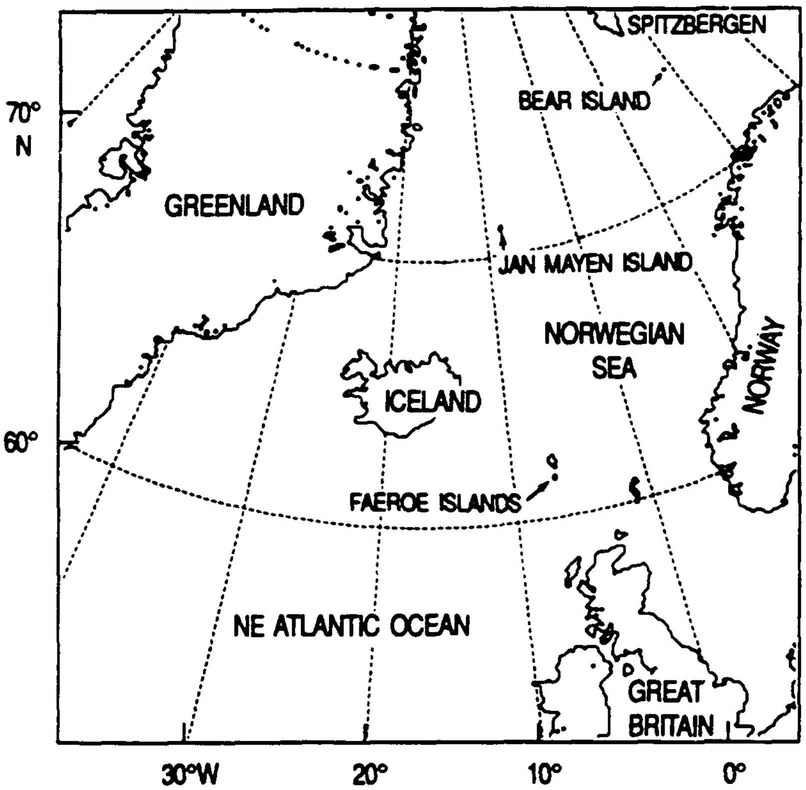
APPROACH

Region

The northeast Atlantic/Norwegian Sea region (Figure 1) provides a relevant as well as challenging environment for evaluating real-time ocean thermal structure products. The area supports major fisheries, includes major transit routes for military and civilian shipping, and provides the source of much of northern Europe's weather.

The Norwegian Sea alone is an extremely complex area as detailed by Hopkins et al. (1986). It is essentially an intermediate ocean that couples the Arctic and Atlantic

FIGURE 1. Geographic area.



oceans. Warm, saline North Atlantic water mixes with cold, fresh Arctic Ocean water resulting in deep water formation and numerous topographically anchored ocean fronts. Dynamic instabilities along these fronts spawn numerous eddies in the region.

Interacting with this complex oceanography is the equally complex meteorology of the region. The climatological division of the atmospheric polar easterlies and the mid-latitude westerlies (the Arctic front) runs approximately southwest to northeast along a line from Iceland through Bear Island. This line roughly coincides with the topographic division of the Norwegian Sea by the mid-Atlantic Ridge and a major ocean frontal division between waters of Atlantic and Arctic origin. The northwestern Norwegian Sea, often called the Greenland Sea, is dominated by northeasterly winds related to Arctic high pressure. These tend to weaken somewhat in summer. The southeastern Norwegian Sea is subject to a sequence of northeastward moving cyclones related to the climatological Icelandic low. These decrease in strength and frequency in spring and summer as the Icelandic low begins to rapidly fill and the polar high builds in March. The filling of the Icelandic low corresponds to the decreasing sea-surface temperature gradient between waters north and south of Iceland. Cyclone strength and frequency again increase in the fall with the increased north to south increase in temperature gradient and the associated renewed deepening of the Icelandic low.

Models

The six thermal structure products available in the Norwegian Sea area are as follows: (1) the FNOC global climatology, (2) the Generalized Digital Environmental Model (GDEM) climatology, (3) the regional Expanded Ocean Thermal Structure (EOTS) real-time nowcast product, (4) the global Optimum Thermal Interpolation System (OTIS) real-time nowcast product, (5) the regional Thermodynamic Ocean Prediction System (TOPS) real-time forecast product, and (6) the global TOPS real-time forecast product.

The two climatologies provide historically averaged thermal structure properties. The FNOC global climatology (Weigle and Mendenhall, 1974) is available monthly on hemispheric polar stereographic grids at 380 km resolution. The GDEM (Teague et al., 1990), provides nearly global coverage at 0.5 degree resolution. GDEM is available monthly at the surface and seasonally below.

The two real-time nowcast products use objective analysis techniques designed to combine the available real-time satellite, ship, buoy, and bathythermograph data with climatological fields to provide a representation of thermal structure in the upper 400 m at a specific time. The EOTS model (Holl et al., 1979), based on the fields-by-information-blending technique, currently runs daily in a region covering the Norwegian and Greenland Seas and northeast Atlantic with grid resolution of ~40 km. The Norwegian Sea EOTS uses the GDEM in its first guess initialization process.

The regional OTIS (Cummings and Ignaszewski, 1991), based on optimal estimation theory, is designed to eventually replace regional EOTS. Presently in the Norwegian Sea region, however, only the global OTIS product is available on a polar stereographic, ~190 km grid for the upper 400 m. The global OTIS uses the coarser resolution FNOC global climatology as its first guess field. Each of these nowcast products, EOTS and OTIS, provides initial conditions for the TOPS daily forecasts for their respective regions.

TOPS is an oceanic mixed-layer forecast model (Clancy and Martin, 1981; Clancy and Pollak, 1983; Martin et al., 1985; Harding and May, 1989) designed to forecast the direct atmospherically forced changes in the upper-ocean temperature and current structure. Forced by the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan et al., 1991), TOPS forecasts run daily (36 hr in the

Norwegian Sea, 72 hr global). The previous day's TOPS 24 hr forecasts feed into a given EOTS (Norwegian Sea) or OTIS (global) nowcast providing upper-ocean information especially in data-sparse areas.

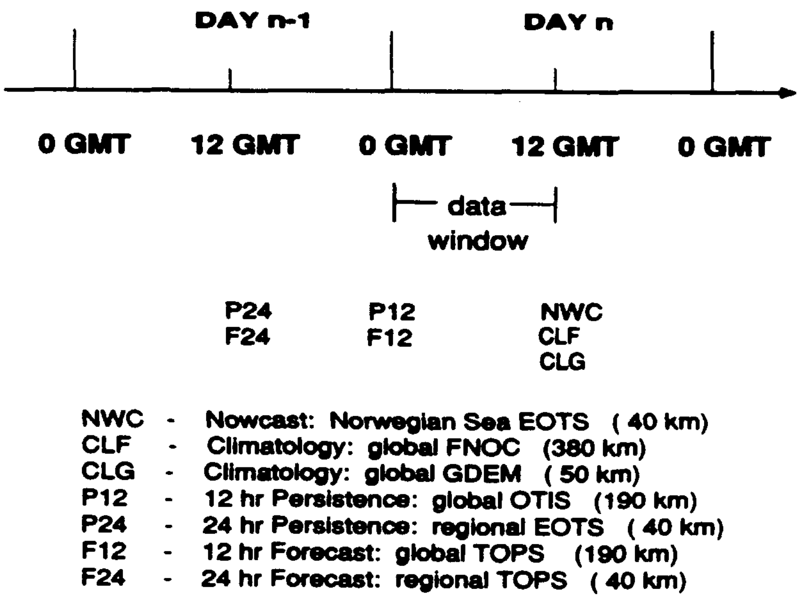
Experimental Design

Consistent with the results of the studies related earlier, we propose two hypotheses. First, the real-time products will demonstrate more nowcast skill than the historically derived climatologies. This improvement in skill should occur if the inclusion of real-time data does indeed provide a better description of the true temporal variability of the ocean. Real-time data, badly aliased in space or time, would degrade a nowcast compared to climatology. Second, the higher resolution real-time products will provide more skillful nowcasts than the global products. These improved nowcasts should result from better resolution of the inherent spatial variability of the ocean. We must also note an uncontrolled confounding variable in testing of the second hypothesis. Previous work (Clancy et al., 1990) indicates that OTIS provides more skillful real-time nowcasts than EOTS when applied to equal grids. Thus, the improvements expected by the higher resolution EOTS products may be partially or completely negated by the advantages of using OTIS for the coarser grid.

To test the above hypotheses, we sampled the available models using the process schematically outlined in Figure 2. At noon Greenwich mean time (GMT) of day n, we saved the accumulated BTs from the previous 12 hrs. As a baseline measure, an EOTS nowcast (NWC) that includes the BT data occurred. The NWC profiles at the BT positions were extracted and saved. The profiles from the climatologies, temporally interpolated to 12 GMT on day n, were taken from both the FNOC climatology (CLF) and GDEM climatology (CLG). Likewise, the profiles at each BT position are extracted from (1) the global OTIS from 12 hrs earlier, namely a 12-hr persistence forecast (P12) and (2) the global TOPS forecast initialized 12 hrs earlier (F12). Both of these forecasts would be valid at noon GMT at day n. The regional products were also sampled, though from 24 hrs earlier. The day n-1 EOTS represented a 24-hr persistence forecast (P24) and TOPS, a 24-hr model forecast (F24).

For this study, we accumulated this daily data for the months from July 1989 through June 1990. We sampled within a 1,000 km radius circle centered between Iceland and the Faeroe Islands (Figure 1). We divided the twelve months of data into three-month groups representing nominal seasons. July, August, and September represent summer. October, November, and December represent autumn.

FIGURE 2. Schematic of temporal sampling.



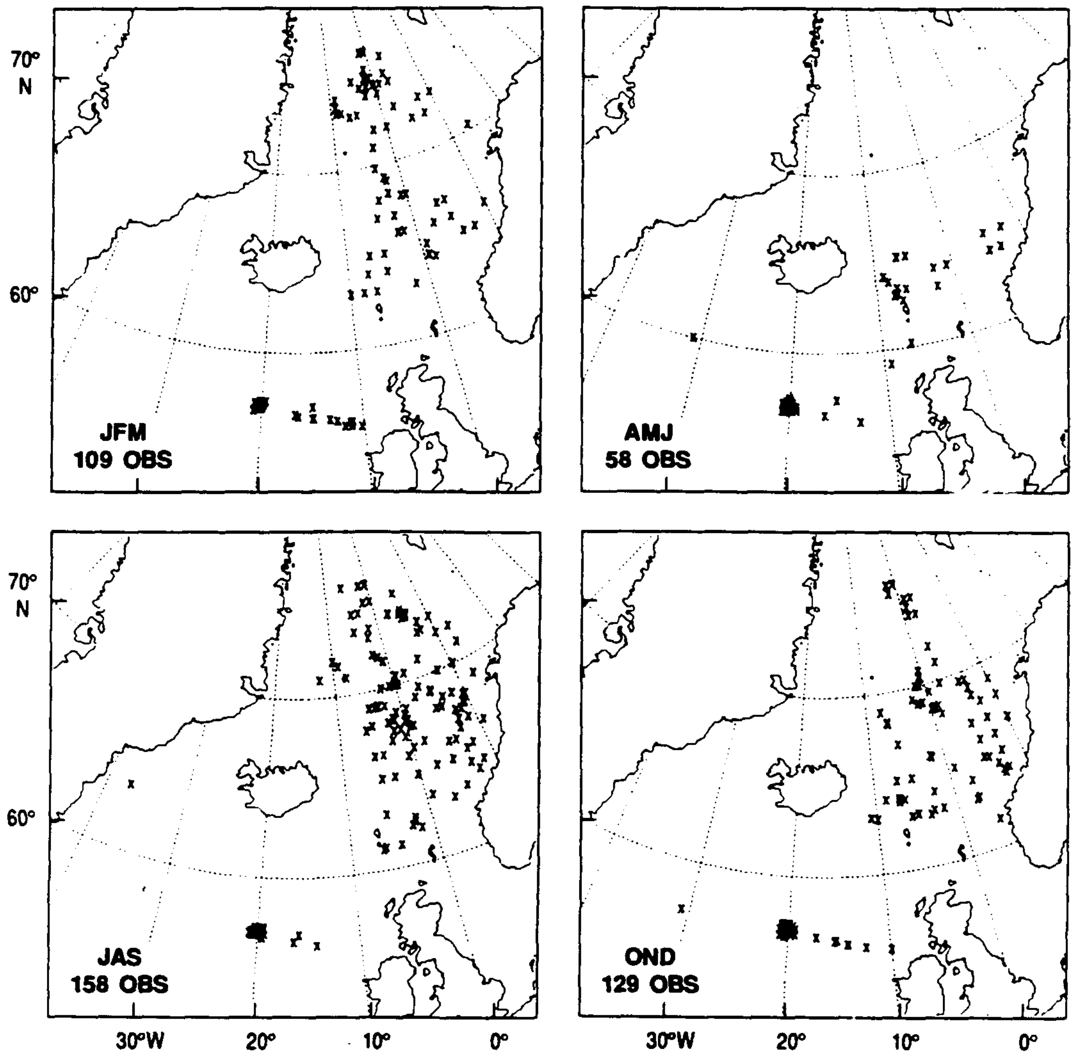
January, February, and March represent winter. And April, May, and June represent spring. We then computed three-month, cumulative statistics including mean, standard deviation, mean error (ME), mean absolute error, and systematic, unsystematic, and total root mean square error (RMSE) (Willmott, 1981, 1982; Willmott et al., 1985). For the purposes of this paper, we focused on the total RMSE as the primary error measure. Due to the unknown distribution of the population, we employed a bootstrap technique (Willmott et al., 1985) to calculate RMSE 90 percent confidence limits.

RESULTS

Figure 3 illustrates the data distribution for each of the four seasons. Sample sizes for each season are 109 for winter, 58 for spring, 158 for summer, and 129 for autumn. The regular sampling at Ocean Station Lima appears as the high density pattern around 57°N and 20°W. Note that the sample sizes are subsets of the actual data available to the real-time analyses. Winter, summer, and autumn samples are about 70 percent of the total available unclassified data. The spring sample is about 45 percent of the available data. These reduced samples occur due to data transmission losses between FNOC and the Naval Research Laboratory. Also for this particular year and in this region, the BT data return drops off dramatically below 150 m. We therefore limited the comparisons to the upper 150 m of the water column.

Table 1 lists the RMSE figures including the 90 percent confidence limits for all six products. Figure 4 shows the RMSE for the

FIGURE 3. Data distribution for (clockwise from upper left) winter, spring, autumn, and summer.

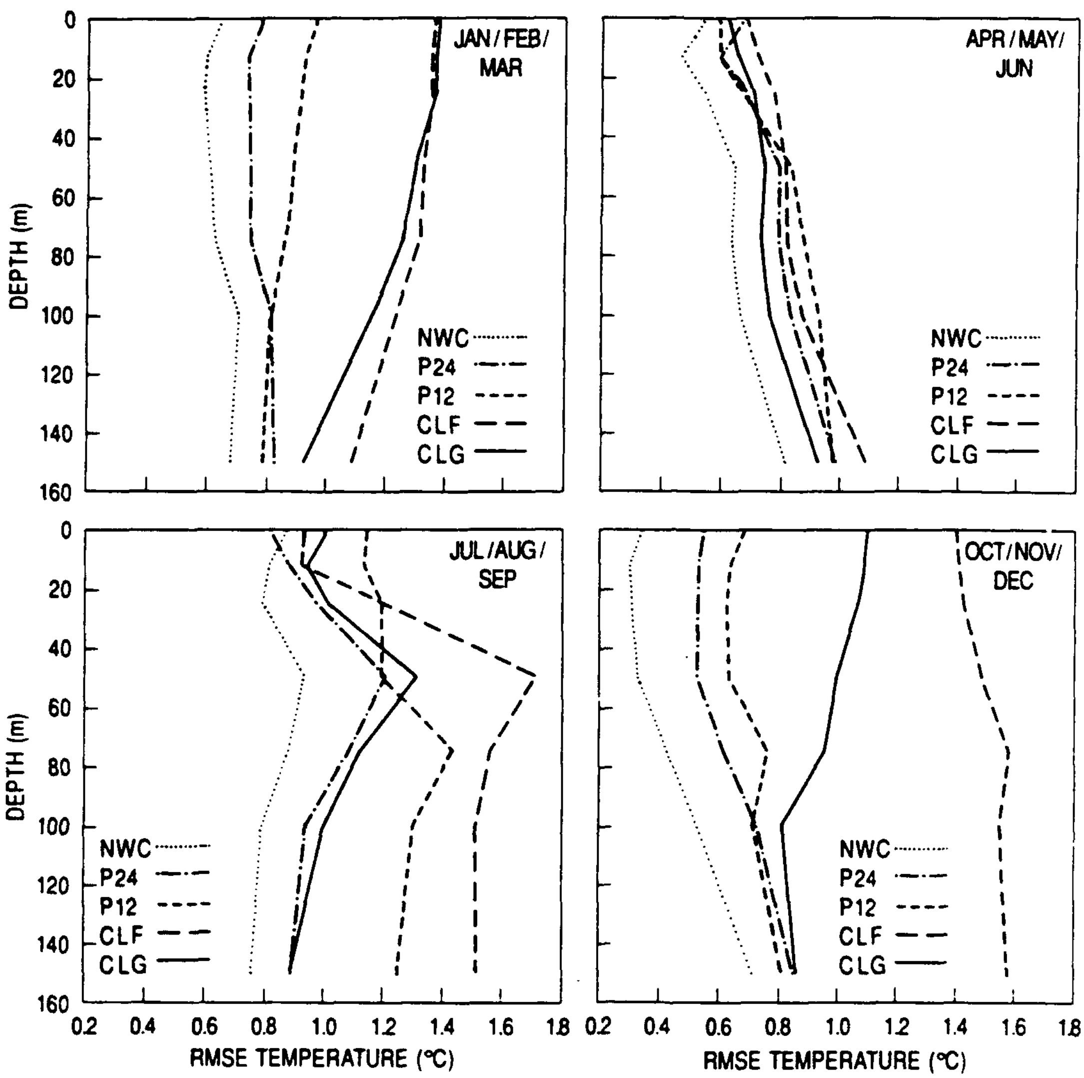


various products with depth. All reported values for RMSE in this paper are in units of degrees Celsius. We dropped the two forecast products from the graphical presentation since they are essentially equivalent to the nowcast results for their respective horizontal resolutions. We expected this since the forecast results, as used here, do not provide temporal interpolations to the BT sampling time. Referring to Figure 2, P24 should be best at 12 GMT on day n-1, F24 should be best at 12 GMT on day n. The various BTs used as comparison, however, are temporally scattered between 0 GMT and 12 GMT on day n. The P12 and F12 are similarly at either end of the sampling period. Future validation tests using the forecast model output at the individual BT sampling time should clarify this issue.

The autumn and winter results from this study clearly support our first hypothesis that real-time products perform better than both climatologies. The RMSE values for both the GDEM climatology (CLG) and the coarser resolution FNOC climatology (CLF) generally range from ~1.3 at the surface to ~1.0 at depth in winter. In autumn, CLG performs better than CLF. CLF ranged from ~1.4 at the surface to ~1.6 at depth while CLG ranged from ~1.1 at the surface to ~0.8 at 100 m and below. The highest real-time product errors (P12) ranged from ~1.0 at the surface to ~0.8 at depth in winter, and from ~0.7 at the surface to ~0.8 at depth in autumn. Only below 75 m in autumn does CLG approach the skill (within the 90 percent confidence bounds) of the real-time products.

In spring and summer, the results are less clear-cut. The spring results all cluster together ranging from ~0.7 at the surface to ~1.0 at depth for all the products. For the summer, the regional P24 performs better than the coarser resolution CLF below 50 m. However, the higher resolution climatology, CLG, tracks very closely with P24. The interesting feature of the

FIGURE 4. Root-mean-square error (° Celsius) versus depth (m) in Iceland/Faeroe region for (clockwise from upper left) winter, spring, autumn, and summer. NWC, P12, P24, CLF, and CLG refer to operational products defined in the text and in Figure 2.



summer plots is the strong increase in RMSE at 50 to 75 m. This depth range coincides with the seasonal thermocline for this area in summer (Hopkins, 1988). The high errors at depth reflect the inability of any of the existing products to resolve the temporal and/or spatial variability of the seasonal thermocline. The forecast models, when used to temporally interpolate to the sample time, should resolve the wind-induced mixed layer variability. This particular capability, however, is not tested by this experiment and requires future study.

Above 100 m, the autumn and winter results also support the second hypothesis that improved resolution of the real-time product improves nowcast skill. The winter regional nowcast (P24) RMSE is ~0.8 from surface to bottom, compared to the coarser resolution P12, which ranges from ~1.0 at the surface to ~0.8 at depth. Autumn RMSE ranges from ~0.6 at the surface to ~0.8 at depth for P24 compared to ~0.7 at the surface to ~0.8 at depth for P12. This result is not as definitive as that with the climatology comparison since the confidence levels must be dropped to about 70 percent to ensure statistical significance. The enhanced skill expected from increased resolution is likely opposed by the increased skill of OTIS versus EOTS (Clancy et al., 1990) as discussed earlier.

In spring and summer, the results are once again mixed. In spring none of the products exhibit an advantage over another as related above. In summer, the higher resolution regional product P24 exhibits ~0.3 degree RMSE improvement over the global P12 at the surface and at depth. However, the scatter of the

TABLE 1. Data for Figure 4 including 90 percent confidence bounds. UL = upper limit, LL = lower limit.

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DEPTH(m)	NWC	P24	F24	P12	F12	CLF	CLG
0.0	0.65	0.79	0.83	0.97	0.99	1.37	1.38
LL	0.45	0.62	0.66	0.84	0.87	1.23	1.18
UL	0.81	0.93	0.97	1.09	1.11	1.51	1.56
12.5	0.60	0.74	0.77	0.93	0.95	1.36	1.37
LL	0.40	0.57	0.60	0.80	0.83	1.22	1.18
UL	0.77	0.90	0.93	1.05	1.07	1.50	1.54
25.0	0.59	0.74	0.76	0.92	0.94	1.36	1.37
LL	0.40	0.57	0.59	0.79	0.82	1.22	1.17
UL	0.77	0.91	0.92	1.05	1.06	1.50	1.52
50.0	0.61	0.75	0.74	0.89	0.90	1.33	1.30
LL	0.40	0.56	0.57	0.76	0.78	1.17	1.10
UL	0.80	0.91	0.89	1.02	1.02	1.48	1.45
75.0	0.63	0.75	0.75	0.87	0.87	1.32	1.26
LL	0.43	0.57	0.57	0.75	0.75	1.17	1.06
UL	0.82	0.92	0.90	0.99	1.00	1.48	1.40
100.0	0.71	0.82	0.82	0.82	0.83	1.24	1.16
LL	0.55	0.66	0.67	0.68	0.71	1.08	0.97
UL	0.89	0.99	0.98	0.94	0.94	1.38	1.30
150.0	0.68	0.83	0.85	0.79	0.77	1.09	0.93
LL	0.55	0.68	0.71	0.67	0.66	0.93	0.81
UL	0.84	0.97	0.99	0.90	0.88	1.23	1.03

APR/MAY/JUN

DEPTH(m)	NWC	P24	F24	P12	F12	CLF	CLG
0.0	0.55	0.68	0.71	0.60	0.65	0.69	0.63
LL	0.42	0.50	0.51	0.48	0.53	0.57	0.50
UL	0.68	0.86	0.90	0.71	0.76	0.81	0.76
12.5	0.47	0.60	0.60	0.60	0.59	0.73	0.66
LL	0.33	0.41	0.40	0.48	0.48	0.63	0.54
UL	0.58	0.78	0.79	0.72	0.70	0.83	0.76
25.0	0.55	0.70	0.69	0.68	0.68	0.78	0.71
LL	0.34	0.40	0.40	0.53	0.53	0.63	0.56
UL	0.75	1.00	0.98	0.82	0.83	0.93	0.88
50.0	0.65	0.80	0.80	0.84	0.83	0.82	0.75
LL	0.40	0.48	0.47	0.57	0.57	0.63	0.53
UL	0.89	1.12	1.12	0.98	0.98	1.04	1.03
75.0	0.64	0.80	0.80	0.88	0.88	0.83	0.74
LL	0.43	0.52	0.53	0.62	0.63	0.66	0.57
UL	0.84	1.06	1.06	1.04	1.04	1/.05	0.94
100.0	0.67	0.84	0.84	0.93	0.93	0.88	0.77
LL	0.48	0.58	0.58	0.67	0.67	0.70	0.65
UL	0.84	1.13	1.13	1.15	1.15	1.13	0.93
150.0	0.82	0.99	0.99	0.98	0.98	1.09	0.93
LL	0.58	0.70	0.70	0.72	0.72	0.83	0.79
UL	1.08	1.32	1.31	1.26	1.26	1.42	1.10

distribution, as represented by the large error limits (Table 1), preclude any statement on the significance of this difference. The errors for the two products converge at the base of the mixed layer, again highlighting the difficulty of representing the seasonal thermocline.

In general, the importance of real-time data and resolution in the autumn and winter results is not apparent in the spring and summer. This difference coincides with the seasonal shift in atmospheric forcing. The incidence and frequency of cyclones decreases significantly while solar heat flux and resultant upper-ocean stratification increases in the spring and summer (Hopkins et al., 1986). This result suggests that the variability in the upper-ocean signal, reflected in the real-time data products in autumn and winter, is atmospherically forced and dominant only in the autumn/winter period.

CONCLUSIONS

The autumn and winter results of this seasonal study in the northeast Atlantic/Norwegian Sea support previous FNOC ocean thermal product validation work demonstrating (1) the statistically significant improvement of the real-time products over climatology and (2) the improvements arising from increased resolution of the real-time products. Results from the spring and summer are inconclusive. Spring and summer also coincide with reduced incidence and strength of cyclones in the area. The difference between autumn/winter and spring/summer results suggest that the variability in the upper-ocean signal resolved by the real-time products is atmospherically driven and dominant only in the autumn/winter period. Summer results also imply limitations in all the products in representing the seasonal thermocline as greater solar heat flux increases upper-ocean stratification.

The overall results provide a valuable quantitative benchmark for proposed upgrades to, or replacements of, existing operational thermal structure products. In addition, they provide an operational frame of reference for research studies in the Norwegian Sea region, such as the recent international Greenland-Iceland-Norwegian (GIN) Sea experiment (G. Heburn, personal communication).

This study supports three major recommendations. First, that FNOC should institute real-time monitoring of the skill of all operational thermal structure products comparable to that done for the global OTIS (Clancy et al., 1992) and Gulf Stream regional OTIS (Cummings and Ignaszewski, 1991). This allows ongoing product skill assessments for all the available operational products. Second, in this ongoing skill assessment, FNOC should include the operational mixed-layer forecast products (including

longer forecasts as well) extracted at the actual BT sample time. This would allow a presently unavailable, ongoing, quantitative measure of skill for the operational forecast products. Third, research into four-dimensional data assimilation using dynamic ocean models and coupled atmosphere/ocean models is needed. This research would allow better representation of the dynamic processes affecting the upper-ocean so that these, too, can be included in future operational products.

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TABLE 1 Continued.

JUL/AUG/SEP

DEPTH(m)	NWC	P24	F24	P12	F12	CLF	CLG
0.0	0.87	0.81	0.81	1.14	0.85	0.93	1.01
LL	0.43	0.57	0.59	0.71	0.67	0.74	0.83
UL	1.15	1.00	0.99	1.53	1.02	1.08	1.20
12.5	0.81	0.89	0.88	1.13	0.83	0.92	0.94
LL	0.51	0.72	0.72	0.74	0.62	0.73	0.78
UL	1.05	1.06	1.04	1.52	1.00	1.07	1.10
25.0	0.79	0.97	0.97	1.19	1.00	1.18	1.01
LL	0.59	0.82	0.82	0.82	0.75	0.91	0.82
UL	0.97	1.11	1.10	1.56	1.24	1.43	1.17
50.0	0.93	1.20	1.20	1.19	1.44	1.71	1.31
LL	0.74	0.99	0.99	0.82	1.21	1.45	1.07
UL	1.11	1.42	1.41	1.56	1.67	1.97	1.52
75.0	0.88	1.08	1.08	1.43	1.38	1.56	1.12
LL	0.70	0.88	0.88	1.09	1.17	1.33	0.91
UL	1.06	1.30	1.30	1.73	1.62	1.78	1.29
100.0	0.79	0.94	0.94	1.30	1.26	1.51	1.00
LL	0.65	0.81	0.81	0.99	1.09	1.31	0.87
UL	0.94	1.09	1.09	1.61	1.41	1.72	1.10
150.0	0.76	0.89	0.89	1.25	1.18	1.52	0.89
LL	0.63	0.80	0.80	0.98	1.04	1.32	0.78
UL	0.89	1.00	1.00	1.54	1.32	1.71	1.00

OCT/NOV/DEC

DEPTH(m)	NWC	P24	F24	P12	F12	CLF	CLG
0.0	0.34	0.55	0.57	0.69	0.87	1.40	1.10
LL	0.30	0.48	0.50	0.58	0.71	1.13	0.88
UL	0.38	0.63	0.64	0.80	1.06	1.69	1.34
12.5	0.30	0.53	0.52	0.64	0.83	1.41	1.09
LL	0.27	0.46	0.45	0.53	0.66	1.13	0.88
UL	0.34	0.60	0.60	0.75	1.01	1.71	1.32
25.0	0.31	0.53	0.52	0.63	0.81	1.43	1.07
LL	0.27	0.46	0.45	0.53	0.65	1.14	0.87
UL	0.35	0.60	0.60	0.73	0.99	1.73	1.29
50.0	0.33	0.53	0.52	0.64	0.82	1.49	1.00
LL	0.30	0.47	0.45	0.55	0.68	1.20	0.85
UL	0.38	0.60	0.59	0.74	0.98	1.81	1.17
75.0	0.43	0.62	0.61	0.77	0.93	1.58	0.96
LL	0.38	0.54	0.53	0.68	0.81	1.31	0.86
UL	0.48	0.70	0.68	0.88	1.08	1.89	1.08
100.0	0.53	0.73	0.72	0.72	0.90	1.55	0.82
LL	0.47	0.64	0.64	0.65	0.80	1.29	0.75
UL	0.61	0.80	0.80	0.80	1.01	1.83	0.92
150.0	0.72	0.86	0.86	0.82	0.96	1.58	0.87
LL	0.60	0.75	0.75	0.73	0.85	1.36	0.78
UL	0.84	0.96	0.97	0.92	1.08	1.85	0.98

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